SUGGESTIONS AS TO THE MODE OF FORMATION OF BARRIER REEFS IN BOUGAINVILLE STRAITS, SOLOMON GROUP.

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[Plate LVIII.]

A broken line of barrier-reef skirts the eastern extremity of the large island of Bougainville at a distance of about fifteen miles from the coast, and incloses a wide expanse of water, forty to fifty fathoms deep, dotted by an archipelago of islands and inlets, mostly of volcanic formation. This line of reef fringes the edge of a sub-marine platform which may be described as the submerged extension of the adjacent coast of Bougainville. On its seaward side the slope of the reef descends rapidly beneath the sea at an angle varying between 15° and 20°, the "hundred fathom" line being removed to between one-quarter and one-third of a mile from the outer edge. Reserving a general description of the reefs of these Straits until the completion of the survey, I will at present confine my remarks to a sub-group known as the Shortland Islands, a collection of islands which have been upheaved along the line of the barrier-reef at the south-west corner of the submerged platform above alluded to.

Viewed from seaward the Shortland Islands have a low-lying level profile never probably attaining an elevation much in excess of 400 feet above the sea. They consist of one main island named Alu (alu), eight to ten miles in length, the coasts of which, more especially those on the weather sides, are skirted by lines of smaller islands and islets. Alu—the main island—is composed in great part of a soft calcareous deposit containing numbers of the shells of pteropods, foraminiferous tests, and other organic

remains, and overlaid by a crust of coral-limestone which probably rarely exceeds a hundred feet in thickness: whilst the lines of islands, which skirt its coasts, are in reality elevated lines of barrier-reefs formed of the coral-rock. The most interesting feature, however, of the geology of this small group of islands—a subject to which I can only briefly refer in connection with the subject of this paper—is the occurrence of volcanic formations in the north-west corner of the main island of "Alu," the volcanic portion passing into the calcareous region of the island without any indication shewn in the profile and surface-contour of such a change of formation.

My examination of the Shortland Islands has led me to the conclusion that they have been formed during a movement of elevation by the advancement of successive lines of barrier-reefs in a prevailing south-eastern direction from the north-west corner of the main island of "Alu," where the volcanic formations occur. The ancient lines of barrier-reefs are still preserved in the interior of this Island by ridges of coral-limestone, which usually have a constant trend at right angles to the prevailing trade-wind The more recent lines of barrier-reefs, which have also experienced elevation, are represented by the broken lines of islands and inlets, some of which rise over a hundred feet above the sea, that skirt the weather coasts of "Alu." The accompanying diagram, which represents a section drawn N.W. to S.E., may make the foregoing remarks more clear. I have purposely drawn it on an exaggerated scale, since on the true scale the more characteristic features could not be delineated.

On the opposite side of Bougainville Straits, a broken line of barrier-reef skirts the western extremity of Choiseul Island inclosing a lagoon-channel known as Choiseul Bay, which has a breadth varying between half and three-quarters of a mile, and a depth in the deeper parts between thirteen and eighteen fathoms, where a sheltered anchorage is obtained. (Vide plan of this locality.) The submarine slope on the outer side of the barrier-reef has a more gradual descent than that which prevails among other reefs of this character in the Solomon Group, the "hundred

fathom" line lying about three-fifths of a mile from the edge of the reef and representing a general inclination of about 10°. The gradual character of the submarine slope of this barrier-reef is a feature on which I lay a particular stress : I have previously referred, in the instance of the long line of barrier-reef on the Bougainville side of the Straits, to the more rapid submarine slope (15° to 20°) as indicated by the nearer approach to the coast of the "hundred fathom" line.

On the line of barrier-reef which incloses Choiseul Bay five wooded islets have been formed. They are for the most part formed of materials thrown up by the waves at the present sea level ; but the presence in some of the larger islets of elevated coral-rock in mass affords evidence of the whole line of reef having been upheaved recently some six feet or more. An islet of coral-limestone, which rises up in the midst of the lagoon-channel to between 20 and 25 feet above the high-tide level, affords testimony of a recent movement of upheaval to that extent. To the northward this line of barrier-reef meets the coast at the head of the bay where it joins the shore-reef ; to the southward, it is continued as a sunken line of reef covered by five or six fathoms of water with a channel thirty fathoms deep inside.

The interior of the adjacent portion of Choiseul Island displays long level ridges with intervening valleys running parallel to the coast—a surface-contour resembling that of the interior of the Shortland Island before described. An examination of the hills near the coast has shown that the geological features are much the same as those of the Shortland Island ; a soft calcareous deposit containing pteropod-shells, foraminiferous tests, and other organic remains, forms the bulk of these hills, being itself encrusted by the coral-limestone. Here then, as in the Shortland Island, barrier-reefs have been formed in a region which has been undergoing upheaval during a prolonged period : but in neither locality was I able to find a clue to the problem of their formation until I had taken a series of soundings off the outer edge of the Choiseul Bay reef, a subject to which I will immediately refer.

The profile, which I have appended, of the seaward slope of this barrier-reef, has been drawn on a true scale, partly from my own soundings which extended to forty fathoms, and partly from those made by the officers of the survey as far as the "hundred fathom line." As shewn in this section, the submarine portion of the reef at first slopes gradually to a depth of four or five fathoms, when it plunges down by a steep declivity another nine or ten fathoms, from the foot of which there is a less precipitous talus-like slope to a depth of about twenty fathoms from the surface. Beyond, there extends a broad ledge covered by from 23 to 25 fathoms of water which terminates in another rapid slope to a depth of a hundred fathoms, which is the limit of the section. Living corals flourish on the upper part of the submarine slope down to the cliff or declivity above referred to. In depths of fifteen to twenty fathoms at the foot of this submarine cliff there appeared to be very little living coral, since out of twelve casts in these depths the armings brought up calcareous sand and gravel on eight occasions. Carrying the soundings further seaward on the broad ledge previously described, I found that the armings of my lead gave much less frequent indications of the occurrence of sand and gravel, whilst the greater proportion of the casts shewed the presence of living coral. Out of eleven soundings in depths between 23 and 40 fathoms, seven shewed a perfectly clean indentation on the arming as of living coral; but on account of the swaying movement of the lead only two of these impressions were recognisable: from a depth of 23 fathoms the prints of the contiguous stars of an Astræa were preserved; and in a subsequent cast of 31 fathoms the impressions of a rounded knob of a Porites with its characteristic small cells were similarly displayed. A reference to the section in profile of this reef will explain this distribution of the detritus and of the living coral.

Sand and gravel, derived from the constant action of the rollers breaking on the edge of the reef-flat, would naturally tend to collect at the foot of the first declivity in depths of fifteen to twenty fathoms; in such a situation living coral would be scarcely expected to thrive; but in the more level region beyond, as the

sand and gravel thinned away, conditions more suitable for the growth of coral would be found, and this is the conclusion towards which my soundings pointed. There would thus appear to exist on the outer submarine slope of this barrier-reef, in depths of fifteen to twenty fathoms, a belt of detritus dividing into two portions the zone in which the reef-building corals thrive. (I have marked the position of this belt in the section by a cross.) Had my soundings been confined to the upper of these two sub-zones, I should have been justified to a great extent, on reaching the belt of sand and gravel, in concluding that coral did not thrive in depths beyond fifteen fathoms; but by subsequently extending such soundings seaward across this band of detritus into the lower or outer sub-zone, I should have exposed the fallacious character of such a conclusion.

The results of these soundings supplied me with an explanation of the growth of barrier-reefs in a region of elevation, which I will briefly review in the light of numerous observations I have made in this group on the growth of coral-reefs during the past two years.

If we imagine an Island, originally formed from the materials ejected from some volcanic vent and bare of coral-reefs, to afford, after the extinction of the subterranean fires, the conditions for growth on its coasts for reef-building corals, a fringing reef of varying width according to the degree of inclination of the submarine slope will ultimately invest its shores. In course of time, the detritus of the corals will collect in a band of calcareous sand and gravel on the outer slope of the reef, marking the apparent limit of the depths in which the reef-corals are usually stated to thrive. But the vertical and horizontal extension of such a band of detritus will be mainly determined, as my observations on the Choiseul barrier-reef have shewn, by the presence and position of submarine declivities and by the degree of inclination of the slope. In such a zone of sand and gravel corals will not thrive; but if the submarine slope has a very gradual inclination, as in the case of the barrier-reef of Choiseul Bay, the lower limit of this zone of detritus may lie within the depths in which reef-building corals flourish, and a line of barrier-reef begin lying parallel with the fringing reef, but separated by a deep channel.

On the other hand, should the submarine slope have a more rapid descent, the lower limit of the belt of detritus may extend far beyond the depths in which reef-corals can thrive: in such a case no barrier-reef will form, and the original fringing-reef will continue to grow outwards on its own talus. On this view the occurrence of barrier-reefs and of fringing-reefs on different parts of the coast of the same island may be readily explained as due to the different degrees of inclination of the submarine slope.

Keeping in view the foregoing explanation of the formation of a barrier-reef in a district which may for a long period have experienced no change in the relative positions of land and sea, we can perceive how in an area of elevation line after line of barrier-reef will be formed as from time to time fresh portions of the sea-bottom, previously below the reef-coral zone, are brought up within the depths in which reefs commence their growth; line upon line of barrier-reef will be thus advanced, each growing up along the lower limit of the belt of detritus derived from the line of reef inside it. In process of time the elevating movement assisted by the accumulation of sediment, the growth of branching corals, and the reclaiming agency of the mangrove, will bring about the filling up of the passages or lagoon-channels between the lines of reef, until at length a tract of land is produced rising gradually from the sea-border to the interior but with the ancient lines of barrier-reef still indicated by ridges of coral-limestone on its surface. Such in fact is in my mind the history of the formation of the Shortland Islands and I opine of the western extremity of the Choiseul Island. In the former locality we have the original Island of volcanic formation in the North-west corner, from which, as from a nucleus, line after line of barrier-reef has been advanced in a south-easterly direction, forming ultimately, during the continuance of the elevation, the large Island of "Alu." Should this elevating movement be at present suspended, as would appear to be indicated by the great width of the reef-flats still over-flowed by the sea on the weather coasts of the outlying islands, there yet remains a considerable addition to be made to the sea-border of "Alu" by the filling up of the passages between the lines of islands which represent

elevated barrier-reefs on its weather coasts. Such a process is in actual operation at the present time in the passages, the encroachment of the mangrove on either side and the upward growth of coral in the channels being the agencies at present effecting this operation. These remarks may be made more clear by a reference to the section of the Shortland Islands.

It follows from this view of the formation of barrier-reefs in this region that the lagoon channels inside the reefs should never be deeper than the zone in which reef building corals are stated to thrive, a depth from which my soundings in different parts of the Solomon Group I place at fifteen fathoms, but which has been variously estimated in other parts of the world, where coral reefs occur, at from ten to thirty fathoms. The passages inside the reefs of the Shortland Islands and Choiseul Bay, comply with this condition. Depths however of forty to fifty fathoms occur, as stated in the commencement of this paper, inside the line of barrier reef that skirts the eastern extremity of Bougainville. Similar depths are not uncommon in the lagoon channels of barrier-reefs in other regions of the Pacific; and thus this view of the formation of barrier-reefs apparently breaks down. There, however, appears to be no "a priori" reason why reef-building corals should not thrive beyond the belt of calcareous sand and gravel that apparently marks the limit of their zone, and therefore in depths greater than those which are usually accepted as favouring the growth of reefs. Soundings off the outer edge of barrier-reefs have rarely been extended (in the Pacific at least) much beyond fifty fathoms, the presence of the sand and gravel, which I hold to be merely gathered together into a belt, having been considered as marking the lower limit of the reef coral zone. I refer not to the soundings taken in a nautical survey which fail to particularize the nature of the bottom with sufficient accuracy, but to such lines of soundings as are taken by observers with a specific object before them.

My observations on the recently elevated calcareous formations of this group enable me to approach this subject by another road; and in passing from the consideration of a probable cause of the

origin of barrier-reefs to the study of such reefs when upraised, with their foundations above the sea, I at once enter a domain of greater certainty. These investigations have shown that coral-reefs are based usually on a partially consolidated calcareous ooze, often foraminiferous, generally abounding with recent shells, and now and then laden with pteropod-shells in considerable numbers, the thickness of the overlying coral-rock rarely exceeding a hundred feet. That the reef-corals commence to grow on such a bottom, and not on a layer of detritus of sand and gravel, is shewn by the fact of my finding at Santa Anna two massive corals of the Astræidæ, the largest four feet in diameter, imbedded in the position of growth, at a height of forty feet above the sea, in the base of a coral-limestone cliff where they almost rested on the subjacent partially consolidated ooze. It is a noteworthy circumstance that in my numerous soundings off the outer edge of reefs in this group, l.c., extending to fifty fathoms, the armings never brought up any other indication of the nature of the bottom, outside the usually accepted coral-zone, than that of calcareous sand and gravel. In truth my soundings down to depths of fifty fathoms failed to reach the ooze. It would therefore appear that such reefs as those of the Shortland Island commenced to build in depths greater than fifty fathoms. If elevation had brought the ooze within these depths uncovered by the calcareous detritus, the armings would probably have recorded such an occurrence amongst some of my numerous soundings. The following question then seems pertinent to the subject in hand. How is it that since coral-reefs base their foundations on calcareous ooze, it is necessary to go far beyond the depths in which reef-corals are usually stated to thrive to reach the ooze. The reply to such a query may furnish a more satisfactory explanation of the depths of forty and even sixty fathoms, which have been found in the lagoon channels of barrier-reefs and in the lagoons of atolls, than those which have been hitherto advanced. Mr. Darwin admitted that an objection to his theory of subsidence might be found in "the circumstance of the lagoons within atolls and within barrief-reefs never having become in any one instance during prolonged subsidences of a

greater depth than 60 fathoms, and seldom more than 40 fathoms" but he met it with the explanation that such lagoons are being filled up, *pari passu* with the downward movement, by the growth of corals and the accumulation of sediment (Coral Reefs, edit., 1842, p. 115.) In the second of two papers by Prof. Arch. Geikie, published in "Nature" (Dec. 6th, 1883) on "The Origin of Coral Reefs," where the arguments for and against the theory of subsidence are fully examined, the more recent views advanced by Mr. Murray and Prof. A. Agassiz are dwelt upon at some length. My observations on the raised calcareous formations in this Group go far to support the modification in Mr. Darwin's theory which appears to have become necessary; but since these observations and my collections are now in the hands of Mr. Murray, I must at present forbear from further remarks on the subject. It may not however, be out of place to observe that amongst the reefs I have examined in this group I have not found evidence of the solution of the coral-rock taking such an important part in the formation of lagoons as is implied in Mr. Murray's description of the reef at Tahiti.

The leading points of my paper I may briefly summarise as follows :—

(1). That reefs of the barrier class exist in Bougainville Straits, a region which has been undergoing upheaval during a prolonged period.

(2). That these reefs may be arranged in two classes, (*a*) those which have been formed at the present sea level; and (*b*) those, which having experienced upheaval, are now represented by lines of islands and islets of coral limestone, varying in elevation between a few feet to over a hundred feet above the sea, their lagoon channels being still preserved but often very shallow.

(3). That the Shortland Islands have been produced by the successive advancements of lines of barrier-reefs from a nucleus of land of volcanic formation during a period of upheaval, a process which resembles that by which,

according to the observations of Professor A. Agassiz, the southern extremity of Florida is growing westward, but with this distinction, that in Florida the area seems to have remained stationary for a long period, the lagoon channels between the concentric lines of reef being merely silted up into dry land.

(4). That the calcareous detritus, which covers the outer slopes of reefs in this group in depths usually of twenty fathoms and beyond, is probably a band dividing the zone of reef-building corals into two sub-zones where the slope is gradual, but where the slope is of a more rapid character extending far beyond the coral zone.

(5). That in the case of reefs which possess such a gradual slope that the lower margin of this band of detritus lies within the zone of reef building corals, a line of barrier-reef will be ultimately formed beyond this band with a deep channel inside : but that in the case of reefs, which possess a more rapid submarine slope so that the lower limit of the band of detritus extends far beyond the depths in which the reef corals thrive, no such line of barrier-reef will be formed.

(6). That where the area is undergoing elevation, a succession of concentric lines of barrier-reefs would thus originate, line after line being advanced, as fresh portions of the sea bottom are brought towards the surface, each line growing upward along the lower margin of the belt of detritus derived from the line of reef inside it.

(7). That inasmuch as my observations go to show that the elevated reefs in this group repose on a partially consolidated calcareous ooze which is not found in depths under fifty fathoms on the outer slopes of the present reefs, it is probable that coral reefs may commence to build in depths greater than those usually assigned.

(8). That on such a view may be readily explained the circumstance, that the depths of the lagoons inside barrier-reefs and atolls so frequently exceed the depths in which reef corals are stated to thrive.

An apparent objection here presents itself with reference to the last two conclusions. If reefs begin to build their foundations in depths greater than those which are usually assigned to them, the thickness of the elevated coral formations I examined ought to have been far in excess of a hundred feet. But fringing reefs themselves are restricted to shallow waters around the coast, and their seaward extension in localities where the submarine slope is steep must be extremely slow. Whilst, on the other hand, in an area of elevation, such as that in which the Solomon Islands are included, barrier-reefs, which begin to grow in depths not less than fifty fathoms, may owe their approach towards the surface as much to the elevating movement as to the very slow upward growth of the coral. It should also be borne in mind that the rapid subaerial denudation to which these regions of heavy rainfall are subjected would be an important agency in the thinning away of the raised coral formations.

In conclusion I may observe that the preceding remarks, although in the main suggestive, are founded on observations not only of reefs as they skirt a coast, but of those whose foundations have been exposed by upheaval. After having failed to account for the origin of the barrier-reefs of Bougainville Straits by the views at present held of the growth of coral reefs, I offer the foregoing explanation of their formation.